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Review

A systematic review and meta-analysis of dynamic tests and related force plate parameters used to evaluate neuromusculoskeletal function in foot and ankle pathology

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ABSTRACT

Background: Force plates are commonly used to register ground reaction forces in order to assess neuromusculoskeletal function of the ankle joint. There exists a great variety in dynamic tests on force plates and in parameters calculated from ground reaction forces in order to evaluate neuromusculoskeletal function of the ankle. The purpose of this study was to evaluate which dynamic tests and force plate parameters are most sensitive to differences between and within groups with regard to foot and ankle pathology.
Methods: A systematic review and meta-analysis was performed evaluating studies that compared force plate parameters of dynamic tests between patients with foot and ankle pathology, and healthy controls. Data were pooled per parameter and test category. Given the clinical heterogeneity, we constructed comprehensive recommendation criteria to indicate a 'proven relevant parameter' or 'candidate relevant parameter'.
Results: A total of 34 studies were included, and 58 relevant comparisons were identified. Results were subdivided by test category: walking, running, landing (in anteroposterior direction), sideways (movement in mediolateral direction) and termination (movement in anteroposterior direction). The 'walking' test showed significant differences in a great variety of pathologies, with the magnitude and timing of the 'second peak vertical force' as proven relevant parameters. The 'landing' test detected differences due to ankle instability, with 'time to stabilization in anteroposterior direction' as proven relevant parameter.
Interpretation: This study provides recommendations concerning the potential of various dynamic tests and force plate parameters as a tool to compare neuromusculoskeletal function between patients with foot and ankle pathology and healthy controls.

1. Introduction

The prevalence of foot and/or ankle pathology due to injury and degenerative disorders is high (Lambers et al., 2012; Thomas et al., 2011). In many cases, these injuries and disorders impair neuromusculoskeletal function and consequently interfere with or even prevent participation in activities of daily life or sports (Thomas et al., 2011). The high prevalence and the associated burden to society have led to great interest among researchers and many studies have attempted to quantify functional deficits in patients.

To quantify impairments of neuromusculoskeletal function in patients with foot and ankle disorders, force plates have been used to register ground reaction forces (GRFs) on the foot while participants perform an activity that challenges neuromusculoskeletal function. The GRF reflects the movement of the whole body that needs to be controlled over base of support provided by the foot or by both feet.

A rough distinction can be made into two types of activities: (quasi-) static and dynamic. In a (quasi-) static test, the participant typically has to maintain his or her balance while standing on either both legs or on one leg, with the eyes open or closed, with or without perturbations (Howells et al., 2011). Given that injuries seldom occur while standing still, it has been argued to test movements that occur during everyday life. This has consequently led to an increase in the number of studies investigating dynamic tests, which consist of an active (e.g. walking or running) or even vigorous (e.g. jump landing or sideways shuffle) movement. In addition to the various dynamic tests, a large number of parameters have been used to characterize the ground reaction force regarding its magnitude, direction, timing and its dynamics (Brown et al., 2008; Dayakidis and Boudolos, 2006; Delahunt et al., 2007; Liu et al., 2012; Ross and Guskiewicz, 2004; Wikstrom et al., 2007).

This abundance of tests and parameters poses a real challenge when designing protocols for research or clinical assessment. Therefore the purposes of this study were to systematically review the

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literature and perform a meta-analysis with regard to dynamic tests using a force plate to evaluate patients with foot and ankle pathology. Specifically, this review attempts to answer the question which dynamic tests, and which force plate parameters are most sensitive to differences between and within groups with regard to foot and ankle pathology. It should be noted that these tests are not used as diagnostic tests to determine the presence or absence of pathology, but to quantify the functional consequences of existing disorders. We make the explicit assumption that foot and ankle disorders do cause neuromusculoskeletal impairments, hence the test or parameter that discriminates better between groups with and without pathology is more sensitive to these neuromusculoskeletal impairments.

2. Methods

2.1. Search strategy

We conducted a literature search using the Cochrane Library, PubMed (Medline), EMBASE, and PEDro databases from inception to January 3rd 2013. The following search strategy was developed for PubMed (Medline): (1) foot OR ankle, (2) forceplate OR force plate OR force platform OR ground reaction force OR ground reaction forces OR kinetic OR kinetics, (3) dynamic OR functional OR gait OR walk OR walking OR run OR running OR step OR stepping OR jump OR jumping OR hop OR hopping OR cut OR cutting OR shuffle, and (4) 1 AND 2 AND 3. For PEDro the following modified search strategy was used: (ankle *force*) OR (foot *force*). Only articles written in English were considered. The reference lists of all included studies were checked for other relevant articles.

2.2. Study selection

Duplicate references were removed from the search results. Two authors (DPF and AH) independently screened the identified articles based on title and abstract to identify potentially relevant articles for extensive review. A study was included if it: (1) compared patients who had a musculoskeletal injury of the foot and/or ankle with healthy controls (between groups) or with the uninjured limb (within group), (2) conducted dynamic tests that involved an active component (e.g. walking, running or jump landing) in contrast to a static test (e.g. single leg stance), and (3) described performance with parameters that can be calculated solely based on force plate data.

We excluded studies that recruited participants that were skeletally immature or had congenital deformities, a neurodegenerative or vascular disease, a history of knee or hip disorders (e.g. osteoarthritis or ligamental tear) or an amputation of any part of the lower extremities. Furthermore, we excluded studies with interventions (e.g. orthotic devices, altered shoes, braces, robotics, crutches, cast) or instigated perturbations (e.g. vibration, nerve stimulation, obstacles, damped surface, slippery surface, uneven terrain, backward gait, added mass, ligament anesthesia) within the study protocol. Finally, we excluded studies that needed additional data (e.g. 3D kinematics) to calculate the parameters used (e.g. joint moments), studies that did not present the mean and standard deviations of the calculated parameters, and studies that had a sample size smaller than six participants per group.

2.3. Data extraction

The extracted data were sample size and participant characteristics, the tests used and instructions given, the comparisons made, the parameters calculated, the group outcome and SD (or an alternative from which SD can be calculated). In addition, the reported significant differences between or within groups were extracted.

2.4. Data analysis

The extracted data were subdivided by test type conducted and into 'between groups' and 'within group' comparisons. Group outcome and SD were imported into Review Manager for a meta-analysis (RevMan, Computer program. Version 5.2. Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2012). The following settings were used: data type — continuous; statistical method — inverse variance; analysis model — random effects; effect measure — std. mean difference; totals — totals and subtotals; study confidence interval — 95%; and total confidence interval — 95%. Consequently, pooled effect size, 95% confidence interval, *P*-value and heterogeneity (I^2) were calculated per test and per parameter. Pooled effect size was interpreted according to Cohen's suggestion: small = 0.20, medium = 0.50, and large = 0.80 (Cohen, 1988). Heterogeneity of outcomes was determined by means of the I^2 test (Higgins et al., 2003).

Our inclusion criteria (diverse pathologies and tests) will in some cases lead to a suboptimal pooling of comparisons and consequently to a high heterogeneity (I^2). Therefore, we constructed comprehensive criteria:

1) A 'proven relevant parameter' showed a significant difference in more than one study, and in at least 50% of the comparisons, plus the pooled effect size was 'large'.
2a) A 'candidate relevant parameter' showed a significant difference in more than one study, and the associated pooled effect size was 'medium' at least, or
2b) showed a significant difference in more than one study and, while the associated pooled effect was not significant, the heterogeneity (I^2) exceeded 60%, or
2c) was used in only one study, which reported a significant difference.

3. Results

3.1. Included studies

The original search identified 3773 articles. After submitting these studies to the selection process (see Fig. 1), we included 34 studies. The characteristics of all studies are presented in Table 1, subdivided by test category, i.e. 'walking', 'running', 'landing' (in anteroposterior direction), 'sideways' (movement in mediolateral direction) and 'termination' (movement in anteroposterior direction). Table 2 provides an overview

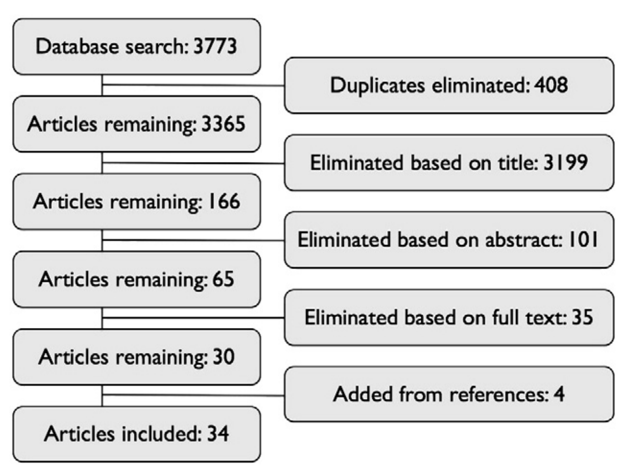

Fig. 1. Flowchart of study inclusion. Reasons for elimination based on full text: No GRF data were presented (15); additional data (e.g. 3D kinematics) were needed to calculate the parameters used (11); literature review (3); perturbation (2); number of participants was less than 6 (2); no comparison between or within groups was made (1); and two studies reporting on the same data, which led to the inclusion of Wikstrom and Hass (2012) and the exclusion of Wikstrom et al. (2010a) (1).

of the distribution of the calculations arranged by pathology and test category. We defined a 'calculation' as the combination of one comparison and one parameter (within one comparison, multiple parameters may have been calculated). Table 3 presents an overview of the operational definitions of the parameters, which are further illustrated in Fig. 2, showing example time series of ground reaction force during each of the five test categories. Tables 4 to 8 present an overview of the parameters that were calculated to evaluate patients with foot and ankle pathology subdivided by test category.

A total of 57 comparisons were identified, of which 9 compared the injured with the uninjured leg ('within group'). The studies concerning these comparisons scarcely presented the SD of the difference. Therefore, it was not possible to include these comparisons in our meta-analysis (hence based on 30 studies). However, the 'within group' comparisons are, together with the 'between groups' comparisons, taken into consideration in our comprehensive criteria.

We noted from our analysis that one study (McCrory et al., 1999) presented with extremely low standard error of the mean (SEM) values for the seven parameters concerning the onset of peak ground reaction forces. Our calculated effect sizes using these SEM values had a range of [−12, −53], which is extremely high and in contrast to the reported non-significances. Although we tried to contact the corresponding author, no elaboration on these inconsistencies was to be obtained. Therefore, we excluded these results from the meta-analysis.

3.2. Pathologies and tests

When the foot and ankle pathologies presented in Table 2 were examined, we observed that the majority of the included studies focused on ankle instability (66% of the calculations). Moreover, the tests 'landing', 'sideways movements' and 'termination' were solely used for ankle instability. In contrast, the 'walking' test was conducted in eight different pathologies, and the 'running' test in five different pathologies. It should be noted that the overall low percentage of significant calculations; the 'walking' test yielded the highest (29%) and the 'running' test the lowest percentage (6%) (see Table 2).

3.3. Walking

All parameters that were calculated to evaluate patients with foot and ankle pathology using a walking test are presented in Table 4 (Brown et al., 2008; Daly et al., 1992; Doets et al., 2007; Fuentes-Sanz et al., 2012; Kitaoka et al., 1994; Liddle et al., 2000; Nuesch et al., 2012; Saw et al., 1993; Skwara et al., 2009; Valderrabano et al., 2007; Wikstrom and Hass, 2012). The operational definitions of these parameters are described in Table 3, Fig. 2A shows an example of a ground reaction force time series.

Among the parameters that reflect the magnitude of the ground reaction force (GRF) in the vertical direction, three parameters showed significant differences in two or more studies and yielded a significant pooled effect. The 'second vertical peak GRF (*Fv.2nd*)' showed a significant difference in 60% of the comparisons and had a large pooled effect size of −1.12. The 'first vertical peak GRF (*Fv.1st*)' and 'midstance vertical valley GRF (*Fv.valley*)' both showed a significant difference in two studies, but in a minority of comparisons (18% and 33%), and yielded pooled effect sizes of −0.43 (small) and 0.72 (medium), respectively.

Among the parameters reflecting the magnitude of the GRF in the anteroposterior (AP) and mediolateral (ML) directions, the 'posterior peak GRF (*Fp.peak*)' and the 'medial peak GRF (*Fm.peak*)' repeatedly showed significant differences, but in a minority of comparisons (44% and 38%, respectively). However, only *Fm.peak* showed a significant pooled effect (−0.51; medium). For *Fp.peak*, the heterogeneity (I^2) was 70%, which indicates a suboptimal pooling of comparisons. This may be explained by pooling the diverse foot and ankle pathologies (i.e. ankle instability, plantar fasciopathy, calcaneal fracture and ankle osteoarthritis) within the 'walking' test category (see Tables 1 and 2). The 'anterior peak GRF (*Fa.peak*)' and 'lateral peak GRF (*Fl.peak*)' both showed a significant difference for just one out of six or more comparisons.

The parameter *Fv.2nd* met the criteria for a proven relevant parameter (significant difference in more than one study, at least 50% of comparisons; pooled effect size: large). The parameters *Fv.valley*, *Fp.peak* and *Fm.peak* met the criteria for candidate relevant parameter.

Some of the studies that used magnitude parameters also calculated the associated 'time to peak GRF' values. One of these, the 'time to second vertical peak GRF (*Tv.2nd*)' met the criteria for proven relevant parameter. This parameter showed a significant difference in two studies and in three out of four comparisons, and resulted in a large and significant pooled effect (−1.03). The other four parameters that showed a significant difference (*time to vertical midstance valley, time to anterior peak, time to posterior peak and time to lateral peak*) all did so in the same single study that compared a non-operatively treated calcaneal fracture with healthy controls and the uninjured limb (Kitaoka et al., 1994). Neither of these parameters yielded a significant pooled effect.

The two parameters that calculated the loading rate did not demonstrate a significant difference.

To summarize, the second vertical peak (*Fv.2nd*) and its associated timing (*Tv.2nd*) met the criteria for proven relevant parameters, whereas the parameters *Fv.valley*, *Fp.peak*, and *Fm.peak* met the criteria for candidate relevant parameters.

3.4. Running

The parameters that were calculated using a running test are presented in Table 5 (Azevedo et al., 2009; Bischof et al., 2010; Brown et al., 2008; Dixon et al., 2006; Hreljac et al., 2000; McCrory et al., 1999; Pohl et al., 2009). The operational definitions of these parameters are described in Table 3, and Fig. 2B shows an example of a ground reaction force time series.

In contrast to the walking test, the parameters that regard the magnitude of the ground reaction force (GRF) did not appear sensitive in the running test. Only the 'first vertical peak GRF (*Fv.1st*)' showed a significant difference, but only in one out of five comparisons, and it yielded a small significant pooled effect (0.33). Additionally the 'lateral peak GRF (*Fl.peak*)' did not show any significant differences, but did yield a small significant pooled effect (0.45). This implies that this parameter might be able to detect differences provided that large numbers of subjects are used.

The parameters regarding time to peak GRF and impulse values did not demonstrate any significant differences between groups, nor did they yield a significant pooled effect.

The parameter 'angle at posterior peak GRF (*Ang.p*)' showed a significant difference, but was only used once. Therefore it met our criteria to be classified as a candidate relevant parameter. The parameter 'loading rate at first vertical peak GRF (*LRv.1st*)' showed a significant difference in two of the five studies (and an equal amount of comparisons), although pooled effect was not significant.

To summarize, none of the parameters met the criteria for proven relevant; the parameter 'angle at posterior peak GRF (*Ang.p*)' yielded a significant difference in the only study it was used in and was therefore classified as candidate relevant.

3.5. Landing

The parameters that have been determined in landing tests are presented in Table 6 (Brown et al., 2004, 2008, 2010; Caulfield and Garrett, 2004; de Noronha et al., 2008; Delahunt et al., 2006; Gribble and Robinson, 2009, 2010; Liu et al., 2012; Ross and Guskiewicz, 2004; Ross et al., 2005, 2008, 2009; Wikstrom et al., 2007; Wikstrom et al., 2010b). The operational definitions of these parameters are described in Table 3, and Fig. 2C shows an example of a ground reaction force time series.

Table 1
Characteristics of included studies.

Study	ID	Instructions	Comparison	Patient group			Control group		
Walking		*Walking speed*		*n*	*Age*	SD	*n*	*Age*	SD
Brown et al. (2008)	1a	1.2–1.4 m/s	Mechanical ankle instability vs copers lateral ankle trauma	21	22.4	4.3	21	21.7	4.9
	1b	1.2–1.4 m/s	Functional ankle instability vs copers lateral ankle trauma	21	22.1	3.8	21	21.7	4.9
Daly et al. (1992)	2	Self selected pace	Postop plantar fasciotomy vs control	9	43.9	13.0		Matched	
Doets et al. (2007)	3	Self selected pace	Postop total ankle arthroplasty (>3 yr) vs control	10	59.8	12.6	10	59.0	12.1
Fuentes-Sanz et al. (2012)	4	Self selected pace	Postop ankle arthrodesis (3 yr) vs uninjured limb	20	40.0	?			
Kitaoka et al. (1994)	5a	Self selected pace	Non-operatively treated calcaneal fracture vs control	16	?	?	110	?	?
	5b	Self selected pace	Non-operatively treated calcaneal fracture vs uninjured limb	16	?	?			
Liddle et al. (2000)	6	Self selected pace	Unilateral plantar heel pain vs uninjured limb	23	44.0	?			
Nuesch et al. (2012)	7	Self selected pace	Posttraumatic unilateral ankle osteoarthritis vs control	8	53.4	11.4	15	48.5	10.5
Saw et al. (1993)	8	Self selected pace	Postop Achilles tendon repair (1 yr) vs uninjured limb	19	37.7	?			
Skwara et al. (2009)	9	Self selected pace	Postop tarsal coalition resection vs uninjured limb	10	25.8	9.5			
Valderrabano et al. (2007)	10a	Self selected pace	Preop total ankle arthroplasty vs control	15	53.3	?	15	52.9	?
	10b	Self selected pace	Postop total ankle arthroplasty (1 yr) vs control	15	53.3	?	15	52.9	?
Wikstrom and Hass (2012)	11a	Self selected pace	Chronic ankle instability vs control	20	20.5	1.0	20	20.9	1.6
Running		*Running speed*		*n*	*Age*	SD	*n*	*Age*	SD
Azevedo et al. (2009)	12	Self selected pace	Achilles tendinopathy (grade I or II) vs control	21	41.8	9.7	21	38.9	10.1
Bischof et al. (2010)	13	3.3 m/s	Second/third metatarsal stress fracture (<5 yr) vs control	9	24.4	6.2	15	22.1	3.4
Brown et al. (2008)	1c	2.5–3.5 m/s	Mechanical ankle instability vs copers lateral ankle trauma	21	22.4	4.3	21	21.7	4.9
	1d	2.5–3.5 m/s	Functional ankle instability vs copers lateral ankle trauma	21	22.1	3.8	21	21.7	4.9
Dixon et al. (2006)	14	3.6 m/s	Third metatarsal stress fracture vs control	10	20.9	2.5	10	23.0	4.6
Hreljac et al. (2000)	15	4.0 m/s	Overuse running injuries (>3 mo) vs control	12	?	?	12	?	?
McCrory et al. (1999)	16	Self selected pace	Achilles tendinitis vs control	31	38.4	1.8	58	34.5	1.2
Pohl et al. (2009)	17	3.7 m/s	Plantar fasciitis (2.8 yr) vs control	25	31.0	10.0	25	31.0	10.0
Landing		*Height/AP distance/action*		*n*	*Age*	SD	*n*	*Age*	SD
Brown et al. (2008)	1e	32 cm/unknown/step down to single leg stance	Mechanical ankle instability vs copers lateral ankle trauma	21	22.4	4.3	21	21.7	4.9
	1f	32 cm/unknown/step down to single leg stance	Functional ankle instability vs copers lateral ankle trauma	21	22.1	3.8	21	21.7	4.9
	1 g	32 cm/unknown/jump to single leg stance	Mechanical ankle instability vs copers lateral ankle trauma	21	22.4	4.3	21	21.7	4.9
	1 h	32 cm/unknown/jump to single leg stance	Functional ankle instability vs copers lateral ankle trauma	21	22.1	3.8	21	21.7	4.9
Brown et al. (2004)	18	50% max/70 cm/jump to single leg stance	Functional ankle instability vs control	10	22.5	2.3	10	21.9	1.0
Brown et al. (2010)	19a	50% max/70 cm/jump to single leg stance	Chronic ankle instability vs control	24	20.0	1.3	24	20.3	1.0
Caulfield and Garrett (2004)	20	40 cm/unknown/jump to single leg stance	Functional ankle instability vs control	14	26.6	6.3	10	22.6	4.6
Delahunt et al. (2006)	21	35 cm/unknown/jump to single leg stance	Functional ankle instability vs control	24	25.0	1.3	24	22.0	0.8
Gribble and Robinson (2010)	22a	50% max/70 cm/jump to single leg stance	Chronic ankle instability vs control	19	20.3	2.9	19	23.1	3.9
	22b	50% max/70 cm/jump to single leg stance	Chronic ankle instability vs uninjured limb	19	20.3	2.9			
Gribble and Robinson (2009)	23a	50% max/70 cm/jump to single leg stance	Chronic ankle instability vs control	19	20.3	2.9	19	23.1	3.9
	23b	50% max/70 cm/jump to single leg stance	Chronic ankle instability vs uninjured limb	19	20.3	2.9			
Liu et al. (2012)	24a	15 cm/leg length/step, step, hop to single leg stance	Functional ankle instability vs control	65	18.2	0.7	65	18.5	1.2
de Noronha et al. (2008)	25	16 cm/unknown/hop to single leg stance	Functional ankle instability vs control	28	26.6	6.9	31	30.0	7.3
Ross and Guskiewicz (2004)	26	50% max/70 cm/jump to single leg stance	Functional ankle instability vs control	14	21.7	2.6	14	22.0	1.9
Ross et al. (2008)	27	50% max/70 cm/jump to single leg stance	Functional ankle instability vs control	15	20.8	2.4	15	20.8	1.8
Ross et al. (2009)	28	50% max/70 cm/jump to single leg stance	Functional ankle instability vs control	22	21.0	2.0	22	21.0	2.0
Ross et al. (2005)	29	50% max/70 cm/jump to single leg stance	Functional ankle instability vs control	10	22.0	2.5	10	20.8	1.3
Wikstrom et al. (2007)	30	50% max/70 cm/jump to single leg stance	Functional ankle instability vs control	54	21.4	1.7	54	20.7	1.2
Wikstrom et al. (2010b)	31	50% max/70 cm/jump to single leg stance	Chronic ankle instability vs control	24	21.7	2.8	24	21.8	2.6
Sideways		*Action*		*n*	*Age*	SD	*n*	*Age*	SD
Brown et al. (2010)	19b	Jump landing to single leg stance/50% max height/70 cm medial	Chronic ankle instability vs control	24	20.0	1.3	24	20.3	1.0
	19c	Jump landing to single leg stance/50% max height/70 cm lateral	Chronic ankle instability vs control	24	20.0	1.3	24	20.3	1.0
Dayakidis and Boudolos (2006)	32a	Run/5.0 m/s/45° forward v-cut on forceplate	Functional ankle instability vs control	15	25.0	5.0	17	23.9	3.8
	32b	Run/5.0 m/s/45° forward v-cut on forceplate	Functional ankle instability vs uninjured limb	15	25.0	5.0			
	32c	Lateral shuffle/crouched position/between forceplates	Functional ankle instability vs control	15	25.0	5.0	17	23.9	3.8
	32d	Lateral shuffle/crouched position/between forceplates	Functional ankle instability vs uninjured limb	15	25.0	5.0			

Table 1 (*continued*)

Study	ID	Instructions	Comparison	Patient group			Control group		
Sideways		*Action*		*n*	*Age*	SD	*n*	*Age*	SD
Delahunt et al. (2007)	33	Lateral hop/30 cm medial/one-legged lateral on and medial off	Functional ankle instability vs control	26	25.6	6.1	24	22.6	4.3
Liu et al. (2012)	24b	Hop landing to single leg stance/5 cm/unknown distance medial	Functional ankle instability vs control	65	18.2	0.7	65	18.5	1.2
	24c	Hop landing to single leg stance/5 cm/unknown distance lateral	Functional ankle instability vs control	65	18.2	0.7	65	18.5	1.2
Termination		*Speed/action*		*n*	*Age*	SD	*n*	*Age*	SD
Brown et al. (2008)	1i	Max run/stop jump to max height/one leg on force plate	Mechanical ankle instability vs copers lateral ankle trauma	21	22.4	4.3	21	21.7	4.9
	1j	Max run/stop jump to max height/one leg on force plate	Functional ankle instability vs copers lateral ankle trauma	21	22.1	3.8	21	21.7	4.9
Brown et al. (2009)	34a	Max run/stop jump to max height/one leg on force plate	Mechanical ankle instability vs copers lateral ankle trauma	21	22.4	4.3	21	21.7	4.2
	34b	Max run/stop jump to max height/one leg on force plate	Functional ankle instability vs copers lateral ankle trauma	21	22.1	3.8	21	21.7	4.2
Wikstrom and Hass (2012)	11b	Self selected walk/planned gait termination	Chronic ankle instability vs control	20	20.5	1.0	20	20.9	1.6
	11c	Self selected walk/unplanned gait termination on audio cue	Chronic ankle instability vs control	20	20.5	1.0	20	20.9	1.6

Characteristics are subdivided into walking, running, landing (in anteroposterior direction), sideways (movement in mediolateral direction) and termination (of movement in anteroposterior direction). The specific *ID* per comparison is intended as a reference with regard to Tables 2, and 4 to 8; *n* is the number of subjects; *Age* is mean age; SD is the standard deviation of the age; yr is year; mo is month; AP distance is the distance in anteroposterior direction.

None of the parameters that quantify the magnitude of the ground reaction force (GRF), showed a significant difference between groups in any study. However, the parameters ‘peak vertical GRF (*Fv.peak*)’ and ‘peak lateral GRF (*Fl.peak*)’ did yield small significant pooled effect sizes of 0.38 and 0.32 respectively. So, while these parameters might be able to show a significant difference when a large number of subjects will be used, they did not meet criteria for proven or candidate parameters.

The associated ‘time to peak GRF’ parameters appeared to be more sensitive; four out of five parameters showed a significant difference once. However, in all cases this was only in a single comparison in a single (but not the same) study. Of these four timing parameters, ‘time to peak vertical GRF (*Tv.peak*)’ and ‘time to peak lateral GRF (*Tl.peak*)’ yielded significant pooled effect sizes, −0.65 (medium) and −0.34 (small), respectively. The pooled effect for the other two parameters, ‘time to anterior peak GRF (*Ta.peak*)’ and ‘time to posterior peak GRF (*Tp.peak*)’, were not significant. The associated heterogeneity (I^2) was 61% for *Ta.peak* and 72% for *Tp.peak*. An explanation for this suboptimal pooling of comparisons is not apparent. As described in Tables 1 and 2, the comparisons using the landing test are all between and within patients with ankle instability.

The stability parameters can be subdivided into two categories: the time to stabilization and the index measures. To start with the first, both ‘time to stabilization in anteroposterior direction (*TTSap*)’ and ‘time to stabilization in mediolateral direction (*TTSml*)’ repeatedly showed significant differences, albeit more in AP direction (71%) than in ML direction (29%). A similar distinction was found with regard to the pooled effect; both were significant, but the *TTSap* yielded a pooled effect size of 0.95 (large) versus 0.40 (small) for the *TTSml*. The combined parameter (*TTSapml*), which is also referred to as resultant vector TTS (time to stabilization) (Gribble and Robinson, 2010; Ross et al., 2008), showed a significant difference in two comparisons (out of three) and yielded a pooled effect size of 0.79 (medium). The second type of stability measures consists of postural stability indices. Indices for the ground reaction force in vertical (*VSI*), anteroposterior (*APSI*), mediolateral (*MLSI*) directions, and a resultant index called the ‘dynamic postural stability index (*DPSI*)’ have been used. The *VSI* and *APSI* showed significant differences in two out of four studies, but did not yield significant pooled effects. However, the heterogeneity (I^2) was 78% for *VSI* and 81% for *APSI*. An explanation for this suboptimal pooling of comparisons is not apparent. All the comparisons were between patients with ankle instability and healthy controls. The *MLSI* showed a significant difference in one study, but no significant pooled effect. The *DPSI* on the other hand, showed significant differences in three (out of four) studies and yielded a small significant pooled effect (0.45).

To summarize, the parameter *TTSap* met the criteria for proven relevant parameters, whereas the parameters *TTSapml*, *VSI*, *APSI* and *DPSI* met the criteria for candidate relevant parameters.

3.6. Sideways

All parameters that were calculated following tests with movements in the mediolateral direction (sideways) are presented in Table 7. These movements include jump or hop landings from medial or lateral direction (Brown et al., 2010; Delahunt et al., 2007; Liu et al., 2012), a v-cut maneuver (Dayakidis and Boudolos, 2006), and a lateral shuffle (Dayakidis and Boudolos, 2006). The operational definitions of these parameters are described in Table 3, and Fig. 2D shows an example of a ground reaction force time series of a lateral shuffle (Dayakidis and Boudolos, 2006).

Among the parameters quantifying the magnitude of the GRF, the parameter ‘first vertical peak GRF (*Fv.1st*)’ showed a significant difference between and within groups, albeit in the same study. The associated pooled effect was not significant. The parameter ‘posterior peak GRF (*Fp.peak*)’ showed a significant difference in the only comparison it was used in. The associated effect size was large (−1.02). The parameter ‘medial peak GRF (*Fm.peak*)’ showed a significant effect, however no significant difference was reported in the study it was used in.

The ‘time to first vertical peak GRF (*Tv.1st*)’ showed significant differences in the same comparisons as *Fv.1st*. Likewise, the associated pooled effect was not significant. However, the associated heterogeneity (I^2) was 79%.

With regard to the stability indices, the *VSI* and *DPSI* each showed one significant comparison out of four comparisons, but without a significant associated pooled effect.

To summarize, the parameter ‘posterior peak GRF (*Fp.peak*)’ showed a significant difference in the only comparison it was used in and therefore qualifies as candidate relevant, no parameters met the criteria for proven relevant.

3.7. Termination

The parameters that were determined following a test based on termination of movement in anteroposterior direction are presented

Table 2
Distribution of calculations, arranged by pathology and test category.

		Walking		Running		Landing		Sideways		Termination			
	ID	*ns*	*s*	*ns*	*s*	*ns*	*s*	*ns*	*s*	*ns*	*s*	*n*	*% sign*
Achilles tendinopathy	8, 12, 16	6		27								33	0
Ankle arthrodesis	4	5										5	0
Ankle arthroplasty	3, 10	8	6									14	43
Ankle instability	[a]	21	1	20		68	23	53	7	28	6	227	16
Ankle osteoarthritis	7	3	3									6	50
Calcaneal fracture	5	14	14									28	50
Metatarsal stress fracture	13, 14			8	1							9	11
Overuse running injuries	15			2	2							4	50
Plantar fasciopathy	2, 6, 17	7	4	1	1							13	38
Tarsal coalition resection	9	3										3	0
n			95		62		91		60		34	342	
% sign			29		6		25		12		18		

A calculation is the combination of one comparison and one parameter (within one comparison, multiple parameters may have been calculated). The specific *ID* per comparison is intended as a reference with regard to Tables 1, and 4 to 8; *ns* is the number of nonsignificant calculations; *s* is the number of significant calculations; *n* is the total number of calculations per pathology or per test; *% sign* is the percentage of significant calculations per pathology or per test.
[a] 1, 11, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34.

in Table 8 (Brown et al., 2008, 2009; Wikstrom and Hass, 2012). As previously discussed, one relevant study (Wikstrom et al., 2010a) was eliminated because it reported on the same data as Wikstrom and Hass (2012). The operational definitions of these parameters are described in Table 3, and Fig. 2E shows an example of a ground reaction force time series of gait termination following walking on self selected pace.

Among the parameters that reflect the magnitude of the GRF, one parameter showed significant differences between groups. The 'posterior peak GRF (*Fp.peak*)' showed differences in one of the two studies it was used in. However, no significant pooled effect size was obtained (0.09). The associated 'time to peak GRF' parameters did not show any significant differences, nor did they yield a significant pooled effect.

Two of the four stability indices showed significant differences in the study they were used in. The *APSI* and the *DPSI* had a significant pooled effect size, 0.47 (small) and 0.53 (medium), respectively.

To summarize, no parameters met the criteria for proven relevant parameters, whereas the parameters *APSI* and *DPSI* met the criteria for candidate relevant parameters.

4. Discussion

This systematic review demonstrated that a wide range of dynamic tests using a force plate as measurement instrument and a variety of associated parameters have been used to compare neuromusculoskeletal function between patients and healthy controls. This emphasizes the added value of this review, but at the same time stresses one of its

Table 3
Operational definitions of the parameters used in the literature.

Parameter	Direction(s)	Description	Test(s)
Magnitude of GRF (%BW; N/kg)			
Peak	V, A, P, M, L, ML	Maximum GRF for associated direction	W, R, L, S, T
Heelstrike peak	V	GRF at impact peak (at approx. 50 ms for V in Fig. 2A)	W
First peak	V, ML	GRF at first peak (at approx. 150 ms for V in Fig. 2A)	W, R, S
Midstance valley	V	GRF at valley (at approx. 350 ms for V in Fig. 2A)	W, R
Second peak	V, ML	GRF at second peak (at approx. 520 ms for V in Fig. 2A)	W, R, S
Mean	A, P, AP, APML	Mean GRF for associated direction	R, L
Standard deviation (SD)	AP, ML, APML	SD of the resultant vector GRF	L
Standard deviation (SD) ln	V, AP, ML	SD of the GRF across trials, averaged over individual point-by-point SD values	T
Coefficient of variation (CV) ln	V, AP, ML	SD normalized to the mean of the score distribution	T
Timing of GRF (ms; s; % gait cycle)			
Time to peak	V, A, P, M, L	Time to maximum GRF for associated direction	W, R, L, S, T
Time to first peak	V, ML	Time to GRF at first peak (approx. 20 ms for V in Fig. 2B)	W, R, S
Time to midstance valley	V	Time to GRF at valley (approx. 50 ms for V in Fig. 2B)	W, R
Time to second peak	V, ML	Time to GRF at second peak (approx. 120 ms for V in Fig. 2B)	W, R, S
Stability (ms)			
Time to stabilization (TTS)	AP, ML, APML	Time until a 3rd order polynomial fit over the rectified GRF intersects a reference value representing the stationary phase	L
Stability index (*VSI*; *APSI*; *MLSI*; *DPSI*)	V, AP, ML, VAPML	Mean square deviations around a zero point for example, $VSI = \sqrt{((sum(((BW - GRFvertical) / BW)^2)) / samples)}$	L
Impulse of GRF (%BW.s)			
Peak; first peak; second peak	V, A, P	Peak GRF × time to peak GRF	R
Loading rate of GRF (%BW/s)			
Heelstrike peak; first peak	V	Peak GRF/time to peak GRF	W, R
Angle of GRF (degrees)			
Peak	A, P	Horizontal projection of GRF relative to the sagittal plane at peak GRF	R

GRF is ground reaction force; *%BW* is percentage body weight; *V* is vertical; *A* is anterior; *P* is posterior; *M* is medial; *L* is lateral; *AP* is anteroposterior; *ML* is mediolateral; *APML* is resultant vector of horizontal GRF; *VAPML* is resultant GRF vector; *ln* is natural logarithm; *W* is walking; *R* is running; *L* is landing; *S* is sideways; *T* is termination.

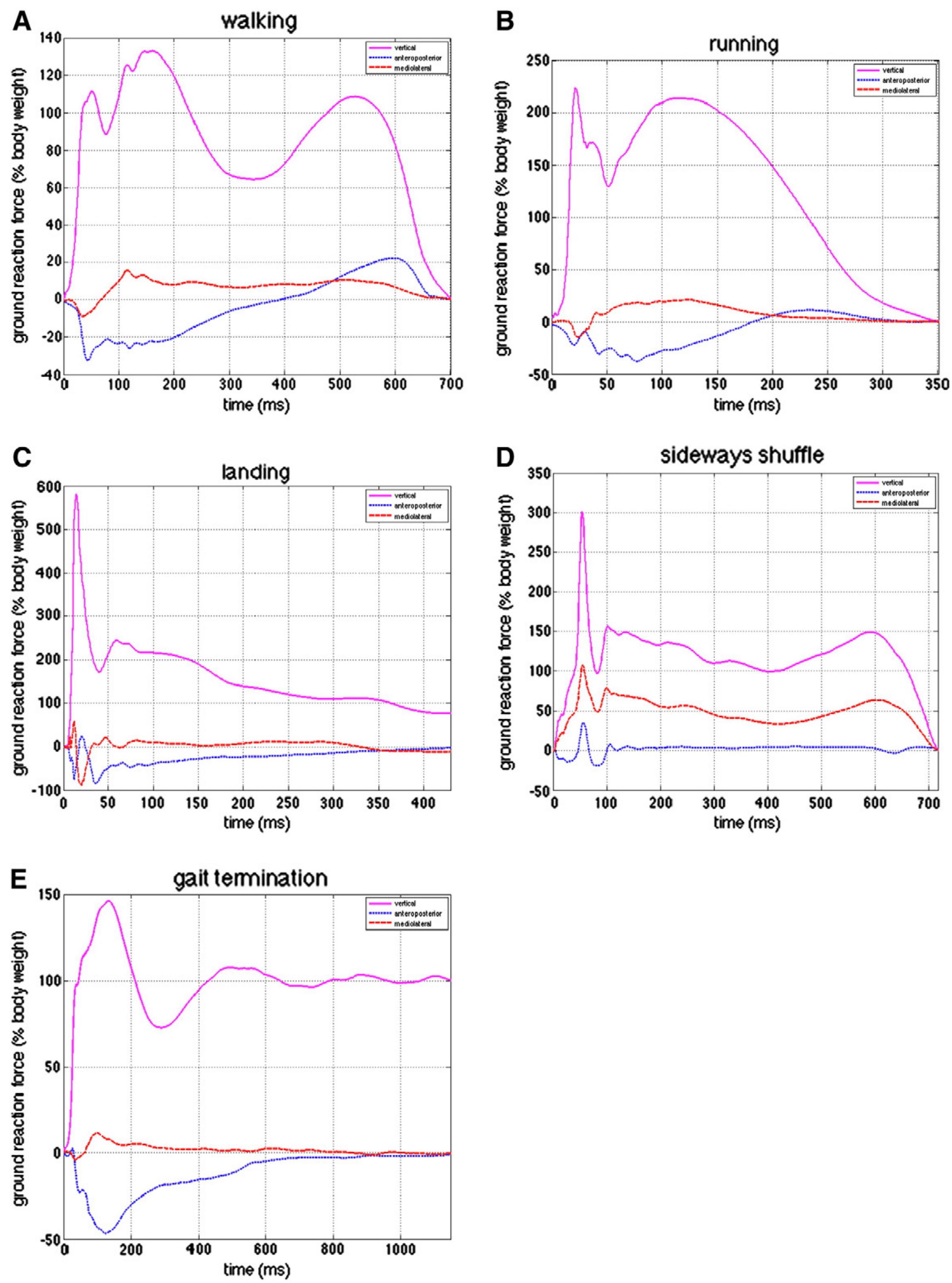

Fig. 2. Typical plots of ground reaction forces during walking at self-selected pace (A); running at self selected pace (B); single leg hop landing from approximately 40 cm posterior and a maximum height of approximately 20 cm (C); sideways shuffle movement, starting medial from the force plate, with a directional change of 180° when the lateral leg is placed on the force plate (D); and the termination of gait (walking at self-selected pace) with one leg on the force plate (E). Positive forces regard anterior and medial direction; negative forces regard posterior and lateral direction.

limitations. The purpose of this study was to identify the dynamic tests and force plate parameters that have been most successful in demonstrating differences between and within groups with regard to foot and ankle pathology. In order to do so, we pooled data of dissimilar comparisons in our meta-analysis. We categorized the comparisons by test and parameter, but did not discriminate between type of foot and ankle pathology, nor with respect to test instruction details, or methodological quality of the included study. The differences in pathologies studied could cause a bias in comparisons of tests and parameters, i.e. when a particular test has only been conducted in studies on a disorder with

Table 4
Parameters that were calculated to evaluate patients with a 'walking' test.

Parameters	Analysis of comparisons (*ID*)		Meta-analysis with regard to 'between' comparisons					
	'Between'	*'Within'*	*n pts*	*n ctrl*	*Pooled ES*	*P-value*	*95% interval*	I^2
Magnitude (*%BW*; *N/kg*)								
Vertical heelstrike peak (*Fv.hs*)		6						
Vertical first peak (*Fv.1st*)	**2**, 3, 5a, **7**, 10a, 10b	4, 5b, 6, 8, 9	73	174	**−0.43**	**0.005**	[−0.73, −0.13]	0%
Vertical midstance valley (*Fv.valley*)*	**2**, **3**, 5a	4, 5b, 9	35	129	**0.72**	**0.01**	[0.14, 1.30]	37%
Vertical second peak (*Fv.2nd*)**	**2**, **3**, **5a**, 7, **10a**, **10b**	4, **5b**, 8, 9	73	174	**−1.12**	<**0.001**	[−1.44, −0.79]	0%
Vertical peak (*Fv.peak*)	1a, 1b		42	42	0.13	0.55	[−0.30, 0.56]	0%
Anterior peak (*Fa.peak*)	1a, 1b, 2, **5a**, 7,1 0a, 10b, 11a	4, 5b, 8	125	226	−0.12	0.54	[−0.51, 0.27]	61%
Posterior peak (*Fp.peak*)*	1a, 1b, **2**, **5a**, **7**, **11a**	4, 5b, 8	95	196	−0.28	0.29	[−0.79, 0.24]	70%
Medial peak (*Fm.peak*)*	1a, 1b, 2, **5a**, **10a**, **10b**	5b, 8	97	191	**−0.51**	**0.03**	[−0.96, −0.06]	61%
Lateral peak (*Fl.peak*)	1a, 1b, 2, **5a**	5b, 8	67	161	0.32	0.05	[0.00, 0.63]	0%
Mediolateral peak (*Fml.peak*)	26		8	15	0.26	0.55	[−0.60, 1.12]	
Time to (*ms*; *s*; *% gait cycle*)								
Vertical first peak (*Tv.1st*)	3, 5a, 7	5b	34	135	0.26	0.56	[−0.63, 1.15]	75%
Vertical midstance valley (*Tv.valley*)	3, **5a**	**5b**	26	120	−0.53	0.25	[−1.42, 0.37]	68%
Vertical second peak (*Tv.2nd*)**	3, **5a**, **7**	**5b**	34	135	**−1.03**	<**0.001**	[−1.62, −0.44]	42%
Vertical peak (*Tv.peak*)	1a, 1b		42	42	−0.14	0.51	[−0.57, 0.28]	0%
Anterior peak (*Ta.peak*)	1a, 1b, **5a**	**5b**	58	152	−0.32	0.37	[−1.03, 0.38]	77%
Posterior peak (*Tp.peak*)	1a, 1b, **5a**	5b	58	152	−0.07	0.76	[−0.56, 0.41]	52%
Medial peak (*Tm.peak*)	1a, 1b, 5a	5b	58	152	−0.21	0.22	[−0.54, 0.13]	0%
Lateral peak (*Tl.peak*)	1a, 1b, **5a**	5b	58	152	−0.17	0.53	[−0.69, 0.35]	59%
Loading rate at (*%BW/s*)								
Vertical heelstrike peak (*LRv.hs*)		6						
Vertical first peak (*LRv.1st*)		6						

The specific *ID* per comparison is intended as a reference with regard to Table 1; *%BW* is percentage body weight; *n pts* is the number of patients; *n ctrl* is the number of controls; *pooled ES* is the pooled effect size; I^2 describes the percentage of total variation across studies that is due to heterogeneity rather than chance; forces in anterior direction describe propulsion, posterior forces represent braking; ** denotes a proven relevant parameter; * denotes a candidate relevant parameter; values shown in italic and bold indicate significance.

Table 5
Parameters that were calculated to evaluate patients with a 'running' test.

Parameters	Analysis of comparisons (*ID*)		Meta-analysis with regard to 'between' comparisons					
	'Between'	*'Within'*	*n pts*	*n ctrl*	*Pooled ES*	*P-value*	*95% interval*	I^2
Magnitude (*%BW*; *N/kg*)								
Vertical first peak (*Fv.1st*)	12, 14, **15**, 16, 17		99	126	**0.33**	**0.01**	[0.07, 0.60]	0%
Vertical midstance valley (*Fv.valley*)	16		31	58	0.16	0.47	[−0.27, 0.60]	
Vertical second peak (*Fv.2nd*)	12, 14, 15, 16		74	101	0.14	0.51	[−0.27, 0.54]	36%
Vertical peak (*Fv.peak*)	13, 1c, 1d		51	57	0.37	0.06	[−0.01, 0.75]	0%
Anterior peak (*Fa.peak*)	12, 13, 1c, 1d, 14, 15, 16		125	158	−0.02	0.91	[−0.32, 0.28]	32%
Anterior mean (*Fa.mean*)	16		31	58	−0.05	0.82	[−0.49, 0.38]	
Posterior peak (*Fp.peak*)	12, 1c, 1d, 14, 16		104	131	0.12	0.43	[−0.18, 0.42]	22%
Posterior mean (*Fp.mean*)	16		31	58	0.52	0.02	[0.08, 0.96]	
Anteroposterior mean (*Fap.mean*)	16		31	58	0.35	0.12	[−0.09, 0.79]	
Medial peak (*Fm.peak*)	1c, 1d, 16		73	100	−0.11	0.47	[−0.42, 0.19]	0%
Lateral peak (*Fl.peak*)	1c, 1d, 16		73	100	**0.45**	**0.005**	[0.14, 0.76]	0%
Time to (*ms*; *s*; *% gait cycle*)								
Vertical first peak (*Tv.1st*)	16							
Vertical midstance valley (*Tv.valley*)	16							
Vertical second peak (*Tv.2nd*)	16							
Vertical peak (*Tv.peak*)	1c, 1d		42	42	−0.39	0.08	[−0.82, 0.04]	0%
Anterior peak (*Ta.peak*)	1c, 1d, 16		42	42	0.05	0.81	[−0.37, 0.48]	0%
Posterior peak (*Tp.peak*)	1c, 1d, 16		42	42	0.06	0.79	[−0.37, 0.49]	0%
Medial peak (*Tm.peak*)	1c, 1d, 16		42	42	0.10	0.66	[−0.33, 0.53]	0%
Lateral peak (*Tl.peak*)	1c, 1d, 16		42	42	−0.01	0.97	[−0.44, 0.42]	0%
Impulse (*%BW.s*)								
Vertical first peak (*Impv.1st*)	16		31	58	0.40	0.08	[−0.04, 0.84]	
Vertical second peak (*Impv.2nd*)	16		31	58	−0.05	0.82	[−0.49, 0.39]	
Anterior peak (*Impa.peak*)	16		31	58	−0.03	0.88	[−0.47, 0.40]	
Posterior peak (*Impp.peak*)	16		31	58	0.00	1.00	[−0.44, 0.44]	
Angle at (*degrees*)								
Anterior peak (*Ang.a*)	14		10	10	−0.50	0.27	[−1.39, 0.39]	
Posterior peak (*Ang.p*)*	**14**		10	10	0.31	0.50	[−0.58, 1.19]	
Loading rate at (*%BW/s*)								
Vertical first peak (*LRv.1st*)	12, 14, **15**, 16, **17**		99	126	0.25	0.14	[−0.08, 0.58]	29%

The specific *ID* per comparison is intended as a reference with regard to Table 1; *%BW* is percentage body weight; *n pts* is the number of patients; *n ctrl* is the number of controls; *pooled ES* is the pooled effect size; I^2 describes the percentage of total variation across studies that is due to heterogeneity rather than chance; forces in anterior direction describe propulsion, posterior forces represent braking; * denotes a candidate relevant parameter; values shown in italic and bold indicate significance.

Table 6
Parameters that were calculated to evaluate patients with a 'landing' test.

Parameters	Analysis of comparisons (*ID*)		Meta-analysis with regard to 'between' comparisons					
	'Between'	*'Within'*	*n pts*	*n ctrl*	*Pooled ES*	*P-value*	*95% interval*	I^2
Magnitude (%BW; N/kg)								
Vertical peak (*Fv.peak*)	1e, 1f, 1 g, 1 h, 20		98	94	**0.38**	**0.01**	[0.09, 0.67]	0%
Anterior peak (*Fa.peak*)	1e, 1f, 1 g, 1 h, 20		98	94	0.06	0.67	[−0.22, 0.35]	0%
Posterior peak (*Fp.peak*)	1e, 1f, 1 g, 1 h, 20		98	94	0.10	0.47	[−0.18, 0.39]	0%
Medial peak (*Fm.peak*)	1e, 1f, 1 g, 1 h, 20		98	94	0.13	0.36	[−0.15, 0.42]	0%
Lateral peak (*Fl.peak*)	1e, 1f, 1 g, 1 h, 20		98	94	**0.32**	**0.03**	[0.03, 0.60]	0%
AP/ML mean res vector (*Fapml*)	25		28	31	−0.09	0.72	[−0.60, 0.42]	
Anteroposterior SD (*SDap*)	25		28	31	−0.10	0.71	[−0.61, 0.41]	
Mediolateral SD (*SDml*)	25		28	31	0.15	0.57	[−0.37, 0.66]	
AP/ML mean res vector SD (*SDapml*)	25		28	31	−0.23	0.38	[−0.74, 0.28]	
Time to (ms; s; % gait cycle)								
Vertical peak (*Tv.peak*)	1e, 1f, 1 g, 1 h, 20, **21**		122	118	**−0.65**	<**0.001**	[−0.92, −0.39]	0%
Anterior peak (*Ta.peak*)	1e, 1f, 1 g, 1 h, **20**		98	94	0.20	0.39	[−0.26, 0.67]	61%
Posterior peak (*Tp.peak*)	1e, 1f, 1 g, 1 h, 20, **21**		122	118	−0.28	0.26	[−0.77, 0.21]	72%
Medial peak (*Tm.peak*)	1e, 1f, 1 g, 1 h, 20, 21		122	118	−0.15	0.25	[−0.40, 0.11]	0%
Lateral peak (*Tl.peak*)	1e, 1f, 1 g, 1 h, **20**, 21		122	118	**−0.34**	**0.009**	[−0.60, −0.09]	0%
Stability (ms)								
Time to stabilization AP (*TTSap*)**	**18**, **23a**, 24a, **26**, **28**, **29**	**23b**	140	140	**0.95**	**0.007**	[0.26, 1.63]	83%
Time to stabilization ML (*TTSml*)	18, 23a, 24a, **26**, **28**, **29**	23b	140	140	**0.40**	**0.04**	[0.03, 0.78]	50%
Time to stabilization AP/ML (*TTSapml*)*	**22a**, **27**	22b	34	34	**0.79**	**0.002**	[0.29, 1.28]	0%
Vertical index (*VSI*)*	**19a**, 24a, **30**, 31		167	167	0.35	0.16	[−0.14, 0.84]	78%
Anteroposterior index (*APSI*)*	19a, 24a, **30**, **31**		167	167	0.50	0.06	[−0.03, 1.02]	81%
Mediolateral index (*MLSI*)	19a, 24a, 30, **31**		167	167	−0.01	0.95	[−0.22, 0.21]	0%
Dynamic index (*DPSI*)*	**19a**, 24a, **30**, **31**		167	167	**0.45**	**0.02**	[0.08, 0.83]	63%

The specific *ID* per comparison is intended as a reference with regard to Table 1; *%BW* is percentage body weight; *n pts* is the number of patients; *n ctrl* is the number of controls; *pooled ES* is the pooled effect size; I^2 describes the percentage of total variation across studies that is due to heterogeneity rather than chance; forces in anterior direction describe propulsion, posterior forces represent braking; ** denotes a proven relevant parameter; * denotes a candidate relevant parameter; values shown in italic and bold indicate significance.

minor effects on neuromusculoskeletal function. To avoid such bias, we considered pooled effects, individual comparisons and heterogeneity of effects in our criteria to assess tests and parameters.

In some cases, high heterogeneity between studies was found, reflecting a suboptimal pooling of comparisons in the meta-analysis. This implies that these effect sizes do not provide valid estimates of the effect of the disorders under investigation. However, we did not aim to infer such clinical information from the pooled comparisons. Instead, we intended to establish evidence that parameters may be useful in demonstrating differences in foot and ankle function. The

Table 7
Parameters that were calculated to evaluate patients with a 'sideways' test.

Parameters	Analysis of comparisons (*ID*)		Meta-analysis with regard to 'between' comparisons					
	'Between'	*'Within'*	*n pts*	*n ctrl*	*Pooled ES*	*P-value*	*95% interval*	I^2
Magnitude (%BW; N/kg)								
Vertical first peak (*Fv.1st*)	**32a**, 32c	**32b**, 32d	30	34	0.40	0.11	[−0.10, 0.90]	0%
Vertical second peak (*Fv.2nd*)	32a, 32c	32b, 32d	30	34	0.36	0.15	[−0.13, 0.86]	0%
Vertical peak (*Fv.peak*)	33		26	24	0.38	0.18	[−0.18, 0.94]	
Anterior peak (*Fa.peak*)	33		26	24	−0.14	0.63	[0.69, 0.43]	
Posterior peak (*Fp.peak*)*	**33**		26	24	**−1.02**	<**0.001**	[−1.61, −0.42]	
Medial peak (*Fm.peak*)	33		26	24	**0.61**	**0.03**	[0.05, 1.18]	
Mediolateral first peak (*Fml.1st*)	32a, 32c	32b, 32d	30	34	0.04	0.87	[−0.45, 0.53]	0%
Mediolateral second peak (*Fml.2nd*)	32a, 32c	32b, 32d	30	34	−0.12	0.63	[−0.61, 0.37]	0%
Time to (ms; s; % gait cycle)								
Vertical first peak (*Tv.1st*)	**32a**, 32c	**32b**, 32d	30	34	−0.43	0.45	[−1.54, 0.68]	79%
Vertical second peak (*Tv.2nd*)	32a, 32c	32b, 32d	30	34	−0.07	0.77	[−0.56, 0.42]	0%
Vertical peak (*Tv.peak*)	33		26	24	0.00	1.00	[−0.55, 0.55]	
Anterior peak (*Ta.peak*)	33		26	24	0.16	0.58	[−0.40, 0.71]	
Posterior peak (*Tp.peak*)	33		26	24	0.00	1.00	[−0.55, 0.55]	
Medial peak (*Tm.peak*)	33		26	24	0.11	0.70	[−0.45, 0.66]	
Mediolateral first peak (*Tml.1st*)	32a, 32c	32b,32d	30	34	−0.17	0.51	[−0.66, 0.33]	0%
Mediolateral second peak (*Tml.2nd*)	32a, 32c	32b,32d	30	34	−0.15	0.55	[−0.64, 0.34]	0%
Stability								
Time to stabilization AP (*TTSap*)	24b, 24c		130	130	0.02	0.93	[−0.45, 0.50]	74%
Time to stabilization ML (*TTSml*)	24b, 24c		130	130	0.03	0.84	[−0.22, 0.27]	0%
Vertical index (*VSI*)	19b, **19c**, 24b, 24c		178	178	0.24	0.18	[−0.11, 0.59]	60%
Anteroposterior index (*APSI*)	19b, 19c, 24b, 24c		178	178	0.42	0.12	[−0.12, 0.95]	82%
Mediolateral index (*MLSI*)	19b, 19c, 24b, 24c		178	178	−0.22	0.24	[−0.59, 0.15]	64%
Dynamic index (*DPSI*)	19b, **19c**, 24b, 24c		178	178	0.08	0.45	[−0.13, 0.29]	2%

The specific *ID* per comparison is intended as a reference with regard to Table 1; *%BW* is percentage body weight; *n pts* is the number of patients; *n ctrl* is the number of controls; *pooled ES* is the pooled effect size; I^2 describes the percentage of total variation across studies that is due to heterogeneity rather than chance; forces in anterior direction describe propulsion, posterior forces represent braking; * denotes a candidate relevant parameter; values shown in italic and bold indicate significance.

Table 8
Parameters that were calculated to evaluate patients with a 'termination' test.

Parameters	Analysis of comparisons (*ID*)		Meta-analysis with regard to 'between' comparisons					
	'Between'	*'Within'*	*n pts*	*n ctrl*	*Pooled ES*	*P-value*	*95% interval*	I^2
Magnitude (%BW; N/kg)								
Vertical peak (*Fv.peak*)	1i, 1j		42	42	0.08	0.71	[−0.35, 0.51]	0%
Anterior peak (*Fa.peak*)	1i, 1j, 11b, 11c		82	82	0.04	0.81	[−0.27, 0.34]	0%
Posterior peak (*Fp.peak*)	1i, 1j, **11b**, **11c**		82	82	0.26	0.09	[−0.04, 0.57]	0%
Medial peak (*Fm.peak*)	1i, 1j		42	42	0.20	0.36	[−0.23, 0.63]	0%
Lateral peak (*Fl.peak*)	1i, 1j		42	42	0.19	0.39	[−0.24, 0.62]	0%
Vertical SD ln (*SDv*)	34a, 34b		42	42	−0.09	0.69	[−0.55, 0.36]	11%
Anteroposterior SD ln (*SDap*)	34a, 34b		42	42	−0.09	0.69	[−0.51, 0.34]	0%
Mediolateral SD ln (*SDml*)	34a, 34b		42	42	−0.10	0.66	[−0.52, 0.33]	0%
Vertical CV ln (*CVv*)	34a, 34b		42	42	0.07	0.83	[−0.57, 0.71]	54%
Anteroposterior CV ln (*CVap*)	34a, 34b		42	42	−0.25	0.54	[−1.05, 0.55]	71%
Mediolateral CV ln (*CVml*)	34a, 34b		42	42	−0.24	0.27	[−0.67, 0.19]	0%
Time to (ms; s; % gait cycle)								
Vertical peak (*Tv.peak*)	1i, 1j		42	42	−0.21	0.33	[−0.64, 0.22]	0%
Anterior peak (*Ta.peak*)	1i, 1j		42	42	0.06	0.84	[−0.53, 0.65]	47%
Posterior peak (*Tp.peak*)	1i, 1j		42	42	−0.40	0.09	[−0.85, 0.44]	7%
Medial peak (*Tm.peak*)	1i, 1j		42	42	−0.03	0.89	[−0.46, 0.40]	0%
Lateral peak (*Tl.peak*)	1i, 1j		42	42	0.03	0.89	[−0.40, 0.46]	0%
Stability								
Vertical index (*VSI*)	11b, 11c		40	40	0.27	0.24	[−0.17, 0.71]	0%
Anteroposterior index (*APSI*)*	**11b**, **11c**		40	40	**0.47**	**0.04**	[0.02, 0.91]	0%
Mediolateral index (*MLSI*)	11b, 11c		40	40	0.15	0.51	[−0.29, 0.59]	0%
Dynamic index (*DPSI*)*	**11b**, **11c**		40	40	**0.53**	**0.02**	[0.08, 0.98]	0%

The specific *ID* per comparison is intended as a reference with regard to Table 1; *%BW* is percentage body weight; *n pts* is the number of patients; *n ctrl* is the number of controls; *pooled ES* is the pooled effect size; s^2 describes the percentage of total variation across studies that is due to heterogeneity rather than chance; forces in anterior direction describe propulsion, posterior forces represent braking; * denotes a candidate relevant parameter; values shown in italic and bold indicate significance.

current recommended parameters are much more likely to be informative compared to the rest of the parameters. It should be noted that the current data are not sufficient to evaluate the clinical utility of a test or parameter for diagnostic purposes.

We not only constructed comprehensive criteria based on the outcomes of the meta-analysis, but also incorporated the number of significant differences reported. The construction of these criteria offered the possibility to include the outcomes of the 'within group' comparison, which had not been incorporated in our meta-analysis, due to fact that the SD of the difference was not reported in most of the studies. Furthermore, these criteria enabled us to evaluate parameters with high heterogeneity. It might be argued that the present findings could be subject to publication bias. However, in orthopedic research the prevalence of publication bias appears low, compared to other fields of medicine (Vavken and Dorotka, 2011). Moreover, Table 2 shows that the majority of reported calculations yielded non-significant differences.

Based on our results, it is possible to provide a recommendation with regard to the choice of dynamic test. The 'walking' test is relatively easy to perform, has been used with uniform test instructions and with a great variety of pathologies, applicable even relatively soon after surgical intervention. The 'running' test most likely requires subjects to have regained at least some function of foot and ankle in order to perform. It has been used with variable running speeds and with a variety of pathologies (however, not after surgical treatment). It could be argued that the tests involving 'landing', 'sideways' and 'termination', require an increased level of foot and ankle function compared to 'walking' and 'running' tests. The 'landing' test has been used with similar instructions, minor differences aside. The 'sideways' and 'termination' tests had a great variety of test instructions. All three tests had a homogenous patient group, solely consisting of ankle instability patients. With the aforementioned notions in mind, it seems that the 'walking' test is best suited to evaluate patients that are judged to be unfit for the more vigorous tests (e.g. 'running', 'landing', 'sideways or 'termination'), for instance those with a severe injury, or those recovering from surgical treatment.

With regard to the 'walking' test, the proven relevant parameters characterize both the magnitude and timing of the 'second vertical peak force' (propulsive phase). All three candidate relevant parameters quantify the magnitude of force, in vertical, posterior and medial directions. The 'running' test was mostly used with patients that suffered from running related injuries, but failed to produce any proven relevant parameters. Furthermore, only the 'posterior peak angle' was categorized as a candidate relevant parameter. An explanation could lie in the variance in running speed together with the limited number of studies. With regard to the 'landing' test, it is important to make a distinction between the impact phase and the stabilization phase of the task. Most of the included studies focused on the stabilization phase, which we consider as a (quasi-) static part of a dynamic task. The proven relevant and candidate parameters all concern this stabilization phase, and it seems that anteroposterior indices perform better than similar indices in mediolateral direction. The 'sideways' test concerns a great diversity of test instructions: jump (Brown et al., 2010) and hop (Liu et al., 2012) landings from medial and lateral direction, a hop-on-hop-off movement in mediolateral direction (Delahunt et al., 2007), a v-cut and a lateral shuffle (Dayakidis and Boudolos, 2006). Only the stability indices have been used in more than one study (see Table 7), and none of these parameters appears to be sensitive to neuromusculoskeletal impairments. Similar remarks can be made with regard to the 'termination' test. This test also has been used with a variety of test instructions in a limited number of studies. However, one could argue that the 'termination' test category is somewhat similar to the 'landing' test category. Keeping this in mind, the fact that the two stability indices that were recommended as candidate relevant parameters, were also recommended as proven relevant parameters in the 'landing' test, strengthens the conclusions on both tests. A limitation is that the pooling of tests with regard to 'termination' can be argued, as a stop-jump task and a gait termination task may differ to some extent. Separating these tasks would not have affected our results. More studies examining these parameters in termination of movement in anteroposterior direction are needed.

With regard to future research and meta-analyses on foot and ankle function, we would like to stress the importance of reporting data sufficiently comprehensive and precise. Also, when a study examines a 'within group' comparison, the presentation of the SD of the differences is necessary, to allow future pooling of outcomes.

In conclusion, this review and meta-analysis provides recommendations concerning the potential of various dynamic tests and force plate parameters as a tool to compare foot and ankle function between patients and healthy controls. The 'walking' test was shown to be able to show significant differences in a great variety of pathologies, with most sensitive parameters being the magnitude and timing of the 'second peak vertical force'. The 'landing' test was shown to be able to detect differences due to ankle instability, with the most useful parameter being 'time to stabilization in anteroposterior direction'. In addition, eleven candidate relevant parameters were identified, of which three concerned the 'walking' test, one concerned the 'running' test, four concerned the 'landing' test, one concerned the 'sideways' test, and two concerned the 'termination' test.

Conflict of interest statement

None of the authors have any personal relationships with other people and organizations that could inappropriately influence or bias this research or the results presented within this manuscript.

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